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Changes in flood events inferred from centennial length streamflow data records

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ABSTRACT

This research examines ways that climate change may alter the risk of flooding in cold regions focusing on changes in the flood regimes and changes and shifts in the dominant flood generating processes at 27 natural watersheds across Canada and the northern United States. Changes in flood regimes are examined using data from long term hydrometric reference streamflow gauging stations whose data record spans the past 100 years; stations included are considered to have good quality data and were screened to avoid the influences of regulation, diversions, or land use change. Changes in flood regimes are complex and require different approaches to properly characterize the variety of changes that have occurred and are likely to occur in the future. Peaks over threshold data are used to explore changes to the magnitude, timing, volume and duration of threshold exceedences. Circular statistics are used to explore changes in the nature of the flood regime based on changes in the timing and regularity of flood threshold exceedences. All flood regimes show an increased number of threshold exceeding events. An increased prevalence of rainfall flood responses is observed as flood events occur more often during the rainfall dominated portion of the seasonal cycle resulting in a shift for nival regime stations to a more mixed regime and for mixed regime stations towards a more pluvial regime. The results support viewing hydrologic regime as a continuum from nival to pluvial with several stations shifting towards the pluvial end.

1. Introduction

The intensification of the hydrologic cycle as a result of climate change has led to concerns that flood events will occur more frequently and increase in magnitude (Milly et al., 2002). Flood events are natural hazards that are both pervasive and complex. The complexity of flood events, including the multiple flood generation processes, implies that flood events will not respond in a uniform manner to changes in climate (Whitfield, 2012). This conclusion is reinforced by the results from two recent papers. Do et al. (2017) analyzed trends in annual maximum daily flow for over 9000 stations around the world and found more stations with significant decreasing trends than stations with significant increasing trends. Hodgkins et al. (2017) examined 1200 stations from North America and Europe and concluded that changes in the occurrence rate of large flood events was more affected by multi-decadal variability than by long term trends.

The focus of this paper is on changes in flood variables within cold region areas of Canada and the northern United States. Changes to floods in cold regions are complicated as a result of the different flood generating processes that can cause flood events within cold regions. Tan and Gan (2015) found evidence of nonstationarity in annual maximum streamflow data for a collection of watersheds from across Canada. They emphasize the need to consider nonstationarity when conducting frequency analysis, especially for watersheds that have experienced land use changes. Rood et al. (2016) examined changes in several flood variables for watersheds from along the continental divide in Canada and the United States. They found more evidence for flood moderation than flood intensification and also identified impacts on flood characteristics related to the Pacific Decadal Oscillation (PDO). Gurrapu et al. (2016) also found the PDO to influence flood magnitudes in a study of watersheds in western Canada. Archfield et al. (2016) examined changes in the frequency, magnitude, duration and volume of flood events across the United States and found that the patterns of changes in flood characteristics were not spatially consistent.

Changes in flood regimes can occur as a result of climate change arising from increased greenhouse gas emissions or through anthropogenic changes to the watershed, such as urbanization or deforestation. Rivers typically have peak flows in specific periods of the year with the exception of floods resulting from infrequent weather events such as hurri-

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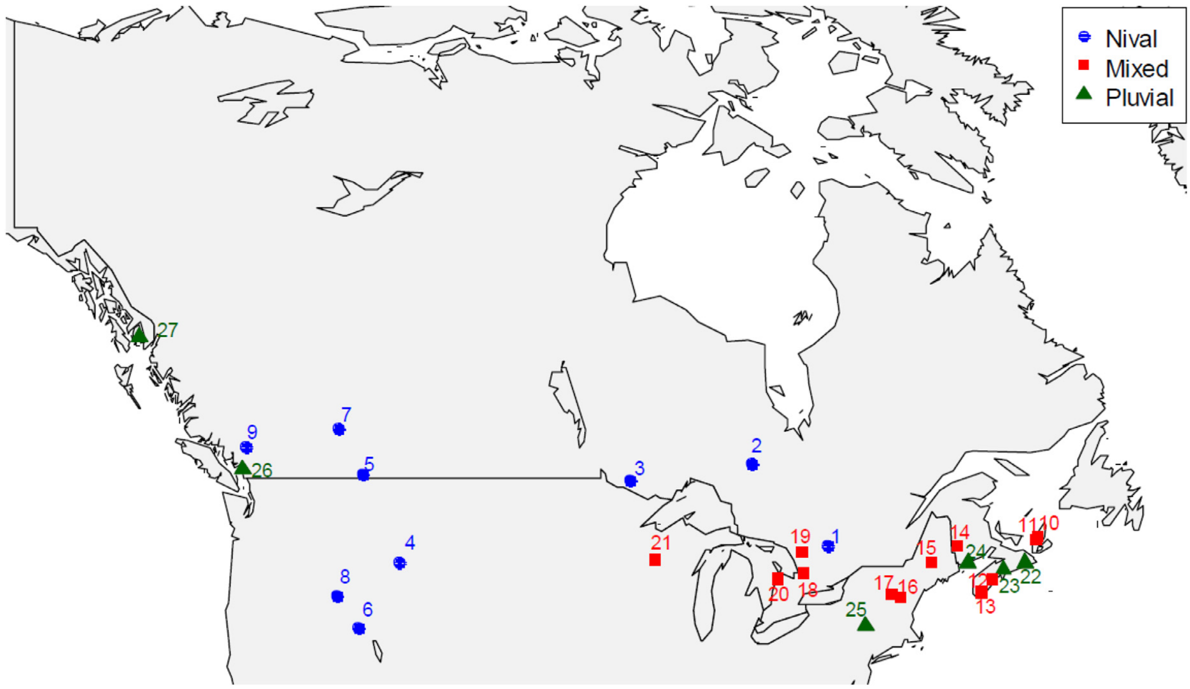

Fig. 1. Location and type classification (nival, mixed, or pluvial) of the 27 reference sites in this study. Numbers provide the Ref. # from Table S1.

canes or atmospheric rivers. This research seeks to identify changes in flood regimes arising from climate change and hence focuses on watersheds for which there have been minimal land use changes so that any observed changes to the nature of flooding events can be inferred to be climate related. To minimize the effects of watershed related changes, only watersheds that are part of a Reference Hydrologic Network (RHN) are included in the analysis. Stations that are part of a RHN are considered to have good quality data and have been screened to avoid the influences of regulation, diversions, or land use change. While it could be argued that there are very few truly pristine watersheds, selecting only watersheds that are part of an RHN reduces the likelihood of the subject watersheds being impacted by non-climate related influences. Whitfield et al. (2012) and Burn et al. (2012) describe the merits of data from an RHN for studies of climate impacts as the effects of land use change are minimized.

Data from stations with long records, nearly 100 years, are used to better characterize the changes that are occurring in flood regimes within the study watersheds. In addition to changes for the entire near-100 year record, trends and changes that would be inferred if only shorter data records were available are investigated through the use of a multi-temporal approach to trend and change analysis. The results from the multi-temporal approach can be used to explore the variability in the drivers of change and highlight the importance of using long term records when exploring changes in hydrologic behaviour. A multi-temporal trend approach has also been used by Schmocker-Fackel and Naef (2010) for flood events in Switzerland, Mediero et al. (2014) for several flood event characteristics in Spain, and Matti et al. (2016) for cold region watersheds in Sweden.

We use peaks over threshold (POT) flood data to capture the complex characteristics of floods; POT data allow us to examine changes in numerous aspects of flood events including measures of the magnitude, frequency, duration, and timing of the over threshold events. POT data have increasingly been used in recent flood studies including Mediero et al. (2014) in Spain, Mallakpour and Villarini (2015) who looked at the central region of the United States, Burn et al. (2016) for Canada, Liu et al. (2017) in China, and Burn and Whitfield (2017) for Canada and northern parts of the United States.

This paper examines changes in cold region flooding and flood regimes for Canada and northern portions of the United States using 27 gauging stations with record lengths that span most of the 100 year period from 1916 to 2015. Choosing stations with nearly 100 years of data allows for the investigation of changes that span several phases of some of the atmospheric drivers influencing flood behaviour. We examine nine flood variables to infer changes occurring in flood event characteristics and explore changes in flood regimes using seasonality measures that describe the timing and regularity of flood events. For the latter analysis, we examine changes based on all flood events for a station and also conduct separate analyses for nival and pluvial flood events.

2. Methods

2.1. Data

The data used in this research are from long term RHN streamflow gauging stations with record lengths that span most of the 100 year period from 1916 to 2015. The data reflect flooding conditions in cold regions of Canada and the northern United States with 18 sites from the Canadian Reference Hydrometric Basin Network (RHBN) (Brimley et al., 1999) and 9 sites from the U.S. Geological Survey (USGS) Hydro-Climatic Data Network (HCDN) (Lins, 2012). Since these time series originate from an RHN, the data from all stations analyzed herein are considered to have good quality data and have been screened to avoid the influences of regulation, diversions, or land use change. These watersheds are the same watersheds reported on in Burn and Whitfield (2017); the details are provided in Table S1 (Table S1 and all Figures denoted "Sx" are contained in the Supplemental Materials).

Each station was classified as to the hydrologic regime of the watershed as nival, mixed, or pluvial using the classification scheme presented in Burn et al. (2016), which uses measures of the annual timing and regularity of flood events to assign a hydrologic regime for a site. Nival watersheds reflect a regime in which flooding events are characteristically the result of snowmelt, pluvial watersheds reflect primarily rainfall flood events and mixed regime watersheds have both snowmelt and rainfall

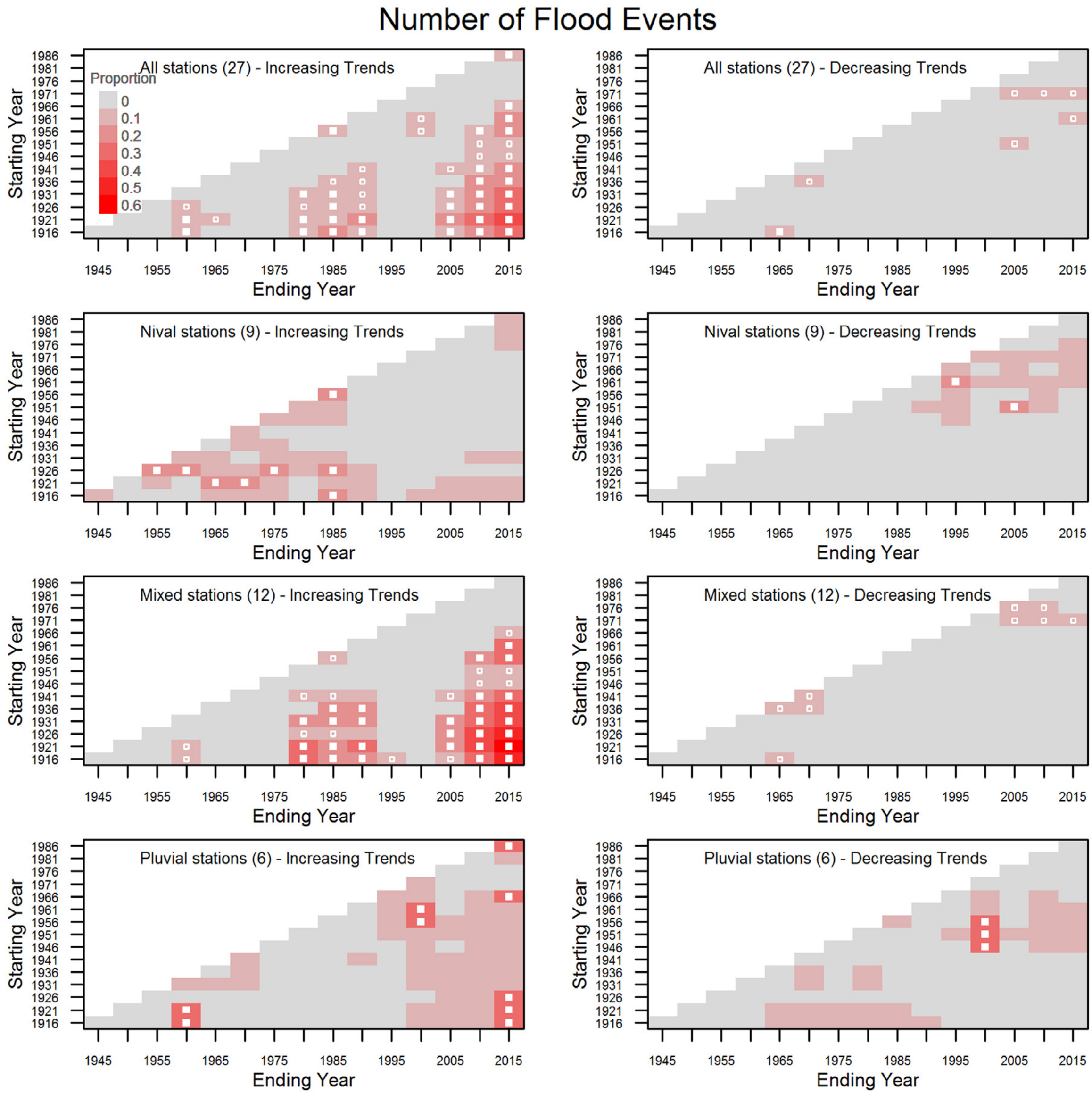

Fig. 2. The proportion of stations showing increasing trends (left column) and decreasing trends (right column) for the number of flood events for all, nival, mixed, and pluvial stations. Boxes along the diagonal are for 30 year periods; the length of periods increases away from the diagonal and is largest in the bottom right corner. Boxes with a solid white square and open square are field significant at 5% and 10% significance levels, respectively.

driven flood events, generally at different times of the year. Although the watersheds are categorized into one of the three indicated hydrologic regimes, it is recognized that hydrologic regime is better viewed as a continuum, as opposed to discrete categories, and furthermore that the hydrologic regime for a watershed can change as a result, for example, of changing climate conditions. While the primary mechanisms of flood generation in these watersheds are snowmelt and rainfall, other generation processes, such as rain-on-snow, occur but cannot be distinguished separately. Determining changes in the hydrologic regime is one of the goals of this research. The locations of the stations used in this research, along with their hydrologic regime, are shown in Fig. 1. The pluvial stations are located on the east and west coasts, the mixed stations are located in the eastern and central parts of the study area and the nival stations are located in the mountainous western part of the study area as well as the more northerly parts of the central section of the study area. The latter group of three stations is an example of why hydrologic regime should be viewed as a continuum in that these stations represent a transition from the pure nival response characteristic of the mountainous nival stations and the mixed regime stations in the central part of the study area.

Peaks over threshold (POT) data were used to better understand the complex nature of flood events, including the magnitude, duration, frequency, and timing of flood events. POT data were extracted from the daily flow data for each watershed using a graphical approach outlined by Burn et al. (2016). The approach ensures independence of over threshold events by specifying a minimal temporal separation of events following recommendations in Lang et al. (1999). POT extraction was facilitated by plots created using the R package "ismev" (Heffernan and Stephenson, 2016). While this approach to extracting POT events is labour intensive, it avoids arbitrarily selecting a threshold based on: i) a specified daily flow percentile (e.g., Vormoor et al., 2016); or ii) a specified average number of events per year (e.g., Mediero et al., 2014). Both of these latter approaches are inappropriate when considering a wide diversity of watersheds, as is the case with our study watersheds, with the presence of different hydrologic regimes and associated flood generation processes.

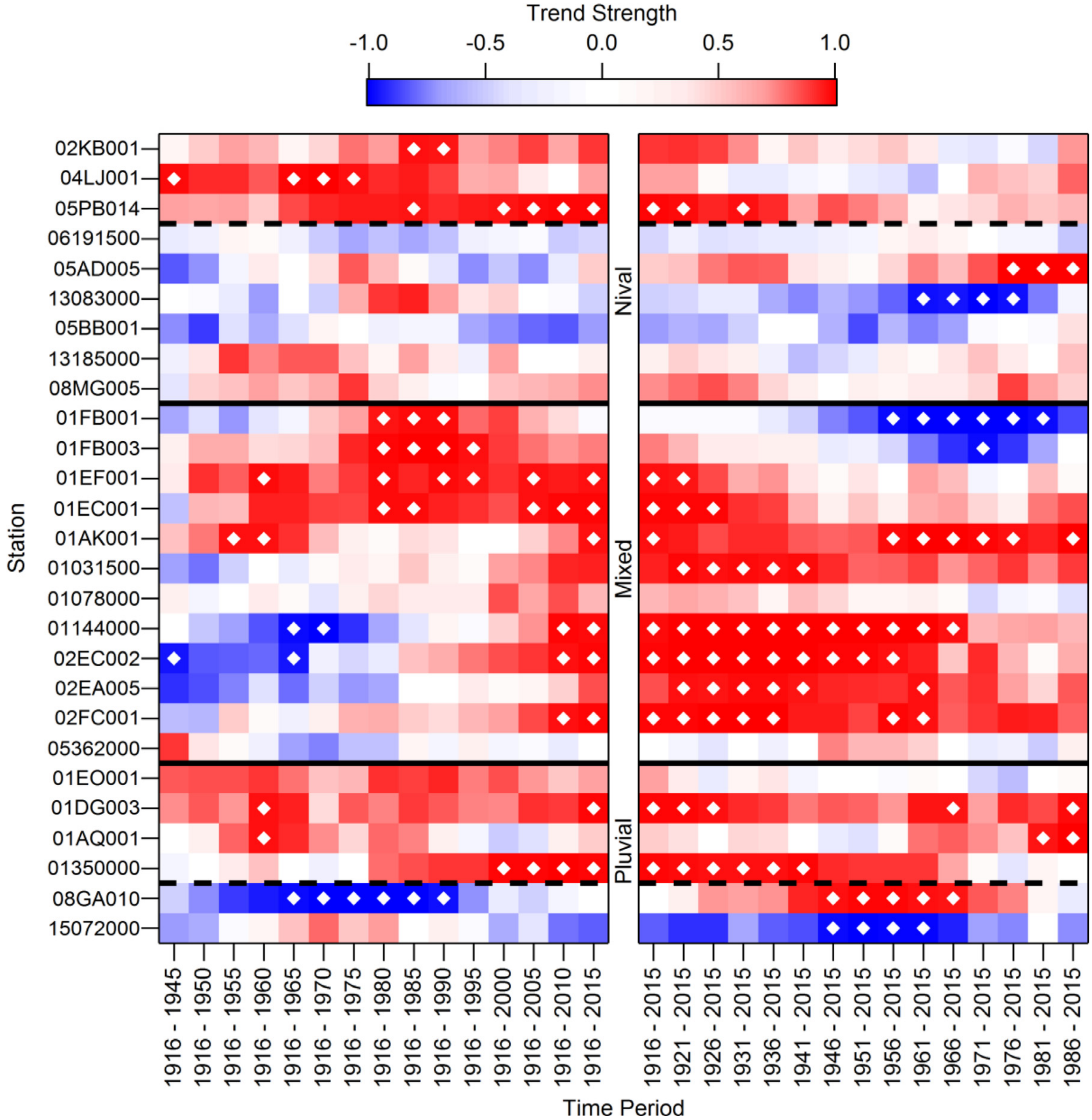

Fig. 3. Trend results for number of flood events for each station. Colours show the strength of the trend and the white diamonds indicate a trend that is significant at the 5% significance level. Nival, mixed and pluvial stations are grouped together and within each group, the stations are ordered from east (top) to west (bottom). The dashed line inside the nival group delineates the mountainous nival stations (lower part) from the non-mountainous nival stations (upper part). The dashed line in the pluvial group separates the two west coast pluvial stations from the four east coast pluvial stations.

2.2. Flood variables

Nine flood variables were defined to examine different aspects of the flood response and changes to the flood response. Six flood variables are calculated on an annual basis and three are defined directly from the series of flood exceedences. The flood variables calculated on an annual basis are: i) the number of threshold exceedences (number of events); ii) the maximum exceedence magnitude (max magnitude); iii) the average exceedence magnitude (average magnitude); iv) the average day of the year of exceedence events (date of occurrence); v) the sum of the event volumes (annual volume); and vi) the sum of the event durations (annual duration). The three event based measures are: i) the flood event magnitude (event magnitude); ii) the flood event volume (event volume); and iii) the flood event duration (event duration). The flood variables and related station information can be found in an online dataset (Burn and Whitfield, 2018).

As well as these nine flood variables, changes in the timing and regularity of the flood response were evaluated using seasonality measures, which afford a more complete examination of the timing of flood events than is embodied in the date of occurrence flood variable. Seasonality measures are derived from circular statistics (Pewsey et al., 2014) based on the dates of flood threshold exceedences. The date of occurrence of a threshold exceedence (flood event) is defined as a directional statistic by converting the Julian date of the threshold exceedence of event i, (January 1 is day 1 and December 31 is day 365 or 366), to an angular value using (Bayliss and Jones, 1993; Burn, 1997):

$$\theta_i = (Julian\ Date)_i \frac{2\pi}{lenyr} \tag{1}$$

where θ_i is the angular value (in radians) for threshold exceedence i and $lenyr$ is the number of days in the year (365 or 366). For a sample of n threshold exceedences, the x- and y-coordinates of the mean date can

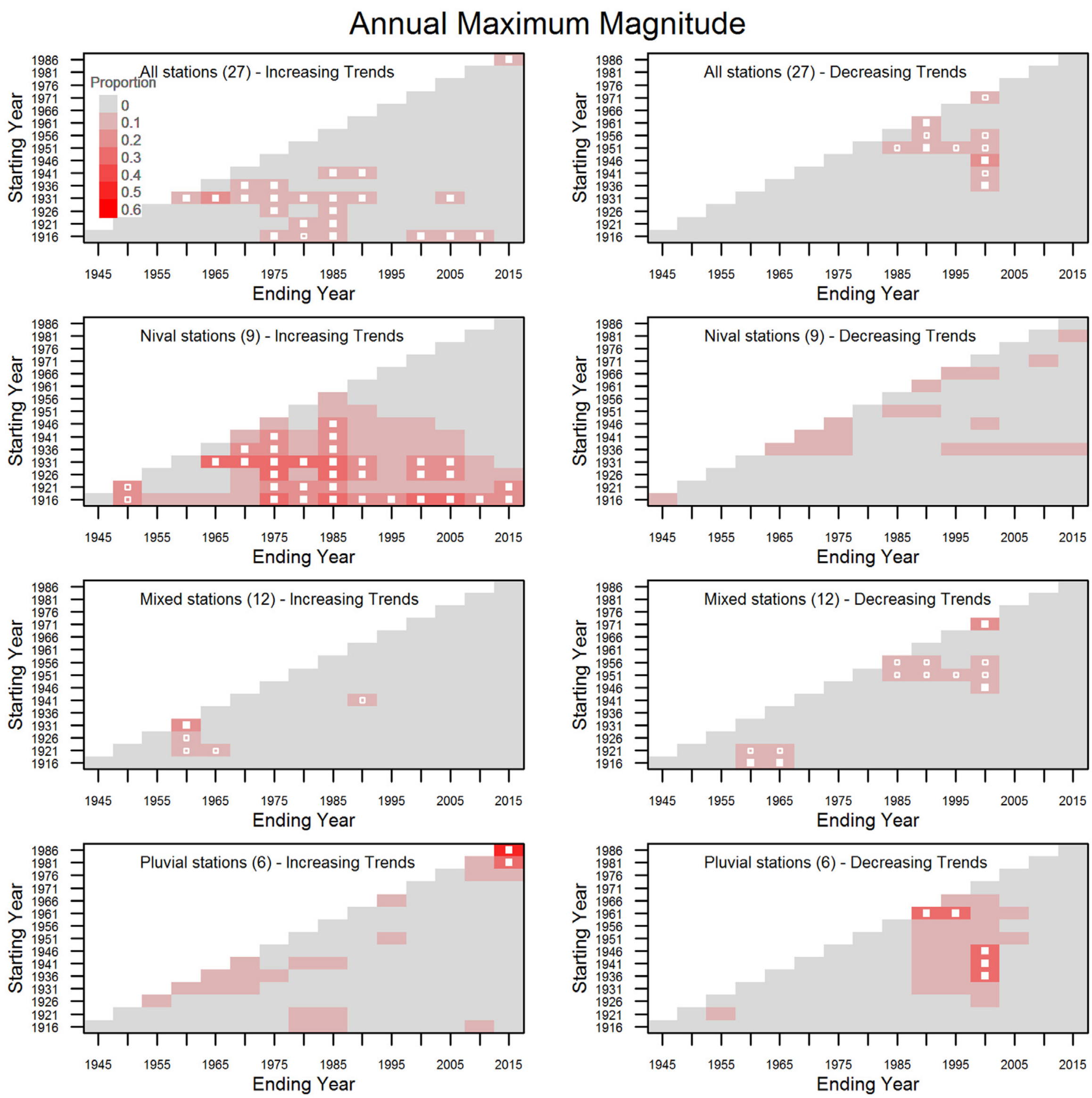

Fig. 4. Same as Fig. 2 but for annual maximum magnitude.

be determined as:

$$\bar{x} = \frac{\sum_{i=1}^{n} q_i \cos\theta_i}{\sum_{i=1}^{n} q_i}; \quad \bar{y} = \frac{\sum_{i=1}^{n} q_i \sin\theta_i}{\sum_{i=1}^{n} q_i} \tag{2}$$

where, following Chen et al. (2013), the relative importance of a threshold exceedence is included through weighting by q_i, which is the magnitude of threshold exceedence i. The mean event date can then be determined as:

$$MD = \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right)\left(\frac{lenyr}{2\pi}\right) \tag{3}$$

where MD is the average date of occurrence of the threshold exceedences. The regularity ($\bar{r}$) of threshold exceedences can be determined from:

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2} \tag{4}$$

where a regularity of 1 indicates that each threshold exceedence occurs on the same day of the year and lower values indicate greater spread in the date of occurrence of the threshold exceedences. When events occur at very different times of the year, the regularity is low, and the mean date may occur at a period of the year when no events are observed. The mean flood event date differs from the date of occurrence flood variable in two important ways. First, while the date of occurrence flood variable is calculated on an annual basis as the simple average of the flood threshold exceedence dates during each year, the seasonality measures are evaluated for a multiple year period with the mean date calculated based on a circular mean, which avoids edge effects inherent in the annual average date of occurrence measure. Second, the inclusion of the magnitude of threshold exceedence in Eq. (2) ensures that smaller flood events are given less importance than larger flood events in defining the timing of flood events.

2.3. Tests for trends and changes

Trends in flood variables that are continuous (max and average magnitude, date of occurrence, annual volume, event magnitude and event volume) were evaluated using the Mann-Kendall non-parametric test for trend (Mann, 1945; Kendall, 1975); block bootstrap resampling (Önös and Bayazit, 2012) was used to correct for serial correlation in the data. Trends in flood variables that are non-continuous (number of

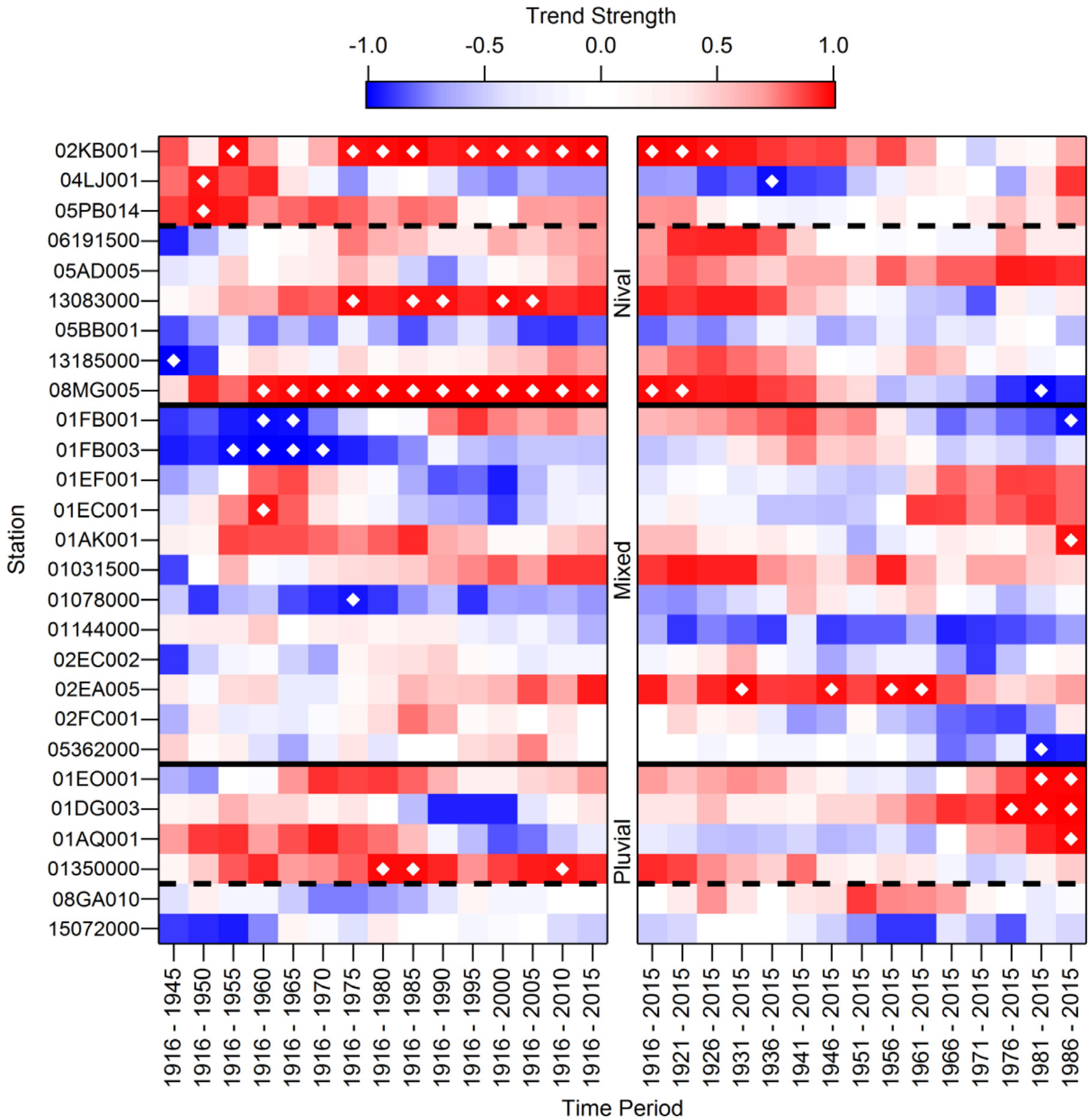

Fig. 5. Same as Fig. 3 but for annual maximum magnitude.

events, annual duration and event duration) were evaluated using logistic regression (Frei and Schär, 2001).

For all trend analyses, field significance was evaluated using vector bootstrapping (Burn and Hag Elnur, 2002; Renard et al., 2008). Field significance determines whether or not the number of stations exhibiting a significant trend is significant. The vector bootstrapping approach creates resampled datasets that preserve the cross-correlation in the original data by sampling data for all sites by year. Field significance of the trend results was evaluated separately for increasing and decreasing trends and was also evaluated for all sites and for the sites classified by hydrologic regime.

The multi-temporal trend approach was implemented by changing the start year for the trend analysis (using five year increments) and considering all possible time windows that have a minimum of 30 years. For the 100 year time period considered herein, there are 120 periods with record lengths varying from 30 to 100 years. For each of the 120 periods so defined, trend analysis is applied for each flood variable and the field significance of the results is ascertained.

Changes in the seasonality of the flood response were examined by calculating the differences in the seasonality measures between an early and a late 30 year period. The starting years for the early and late periods are separated by at least 30 years with the separation between periods (end of early period to start of late period) ranging from 0 to 40 years, in five year increments. This results in 45 separate change evaluations for the multi-temporal analysis. The significance of the changes in the timing (mean date) and regularity ($\bar{r}$) between the early and late periods was evaluated by comparing the observed change to the distribution of changes estimated through a resampling approach. In the resampling approach, 60 years are selected at random from the 100 year period and half of the years are randomly assigned to the "early" period and half to the "late" period. Changes in the mean date and regularity are determined for each resampled dataset from which the distribution of the changes is estimated. Field significance for the change analysis was conducted following an analogous approach to that outlined above for trend analysis.

Changes in seasonality were explored using three versions of the dataset of threshold exceedences. The analysis was first performed using

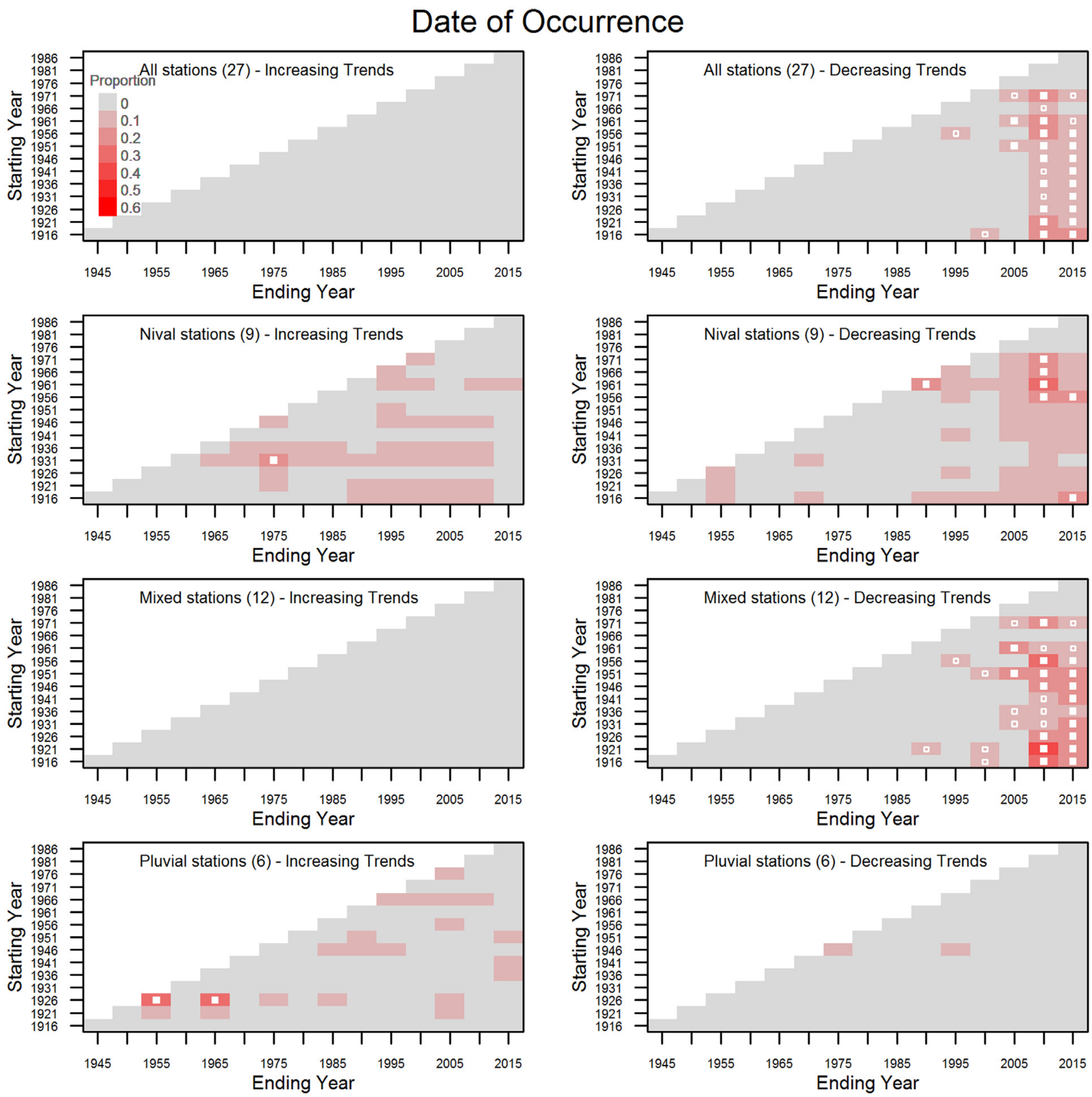

Fig. 6. Same as Fig. 2 but for date of occurrence.

all data with the intent of exploring overall changes in seasonality and hence in the flood generation processes. The second and third datasets consist of the data segregated into snowmelt (nival) events and rainfall (pluvial) events, respectively. These latter two datasets facilitate the examination of changes within a primary flood generation process (e.g., are snowmelt events occurring earlier in the most recent part of the record?). The separation of the events into snowmelt and rainfall events was done using a clustering algorithm applied to the dates of threshold exceedences (see Whitfield, 2017) using Partitioning Around Medoids (pam) from the R package “cluster” (Maechler et al., 2017).

Table 1

Percentage of sites with significant increasing (decreasing) trends for the flood variables for the period 1916–2015. Numbers of stations are shown in [].

	All sites [27]	Nival [9]	Mixed [12]	Pluvial [6]
Number of events	***33.3*** (0.0)	11.1 (0.0)	***50.0*** (0.0)	***33.3*** (0.0)
Max magnitude	7.4 (0.0)	***22.2*** (0.0)	0.0 (0.0)	0.0 (0.0)
Average magnitude	7.4 (0.0)	***22.2*** (0.0)	0.0 (0.0)	0.0 (0.0)
Date of occurrence	0.0 ***(18.5)***	0.0 ***(22.2)***	0.0 ***(25.0)***	0.0 (0.0)
Annual volume	3.7 (0.0)	0.0 (0.0)	0.0 (0.0)	16.7 (0.0)
Annual duration	***11.1*** (0.0)	0.0 (0.0)	***16.7*** (0.0)	16.7 (0.0)
Event magnitude	7.4 (3.7)	11.1 (0.0)	8.3 (8.3)	0.0 (0.0)
Event volume	3.7 ***(11.1)***	0.0 (11.1)	8.3 ***(16.7)***	0.0 (0.0)
Event duration	0.0 ***(14.8)***	0.0 (11.1)	0.0 ***(25.0)***	0.0 (0.0)

Entries in ***bold italics*** are field significant (10% significance level)

3. Results

3.1. Trend results

Table 1 summarizes the trend results for the nine flood variables based on the period 1916 – 2015. Shown in Table 1 is the percentage of stations with a significant trend (5% local significance level) with results provided separately for increasing versus decreasing trends. Field significance, evaluated at the 10% significance level, is also indicated in Table 1. The trend results reveal strong increases in the number of

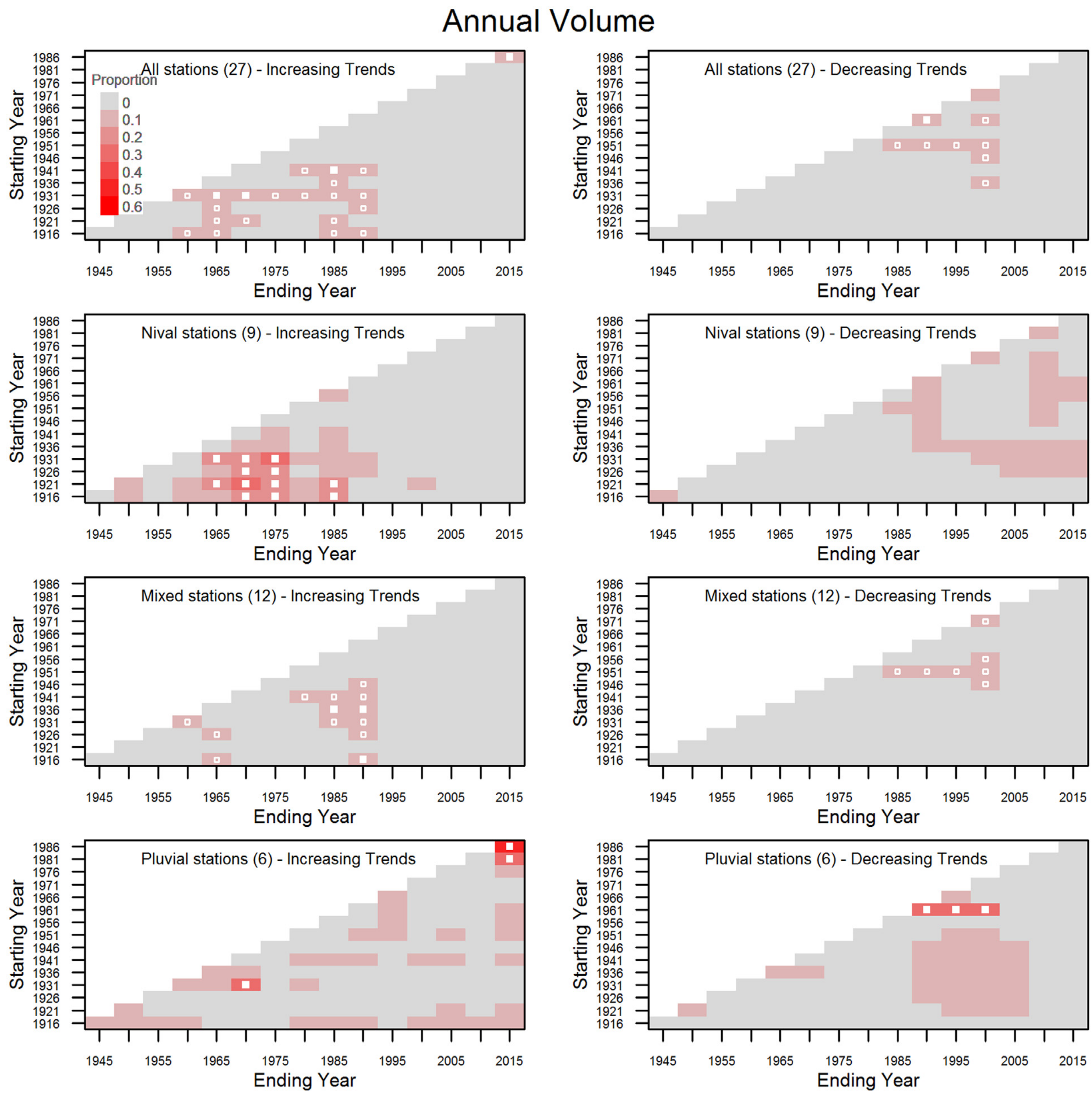

Fig. 7. Same as Fig. 2 but for annual volume.

events with this trend arising primarily from the mixed regime and, to a lesser extent, the pluvial regime. The maximum and average magnitudes of flood events are increasing in the nival regime; this may be a result of the main melt component happening in a briefer period of time in a warmer climate or changes to rain-on-snow events, but this requires further research. The date of occurrence is decreasing (earlier occurrence of flood events) with this taking place for nival and mixed regimes. There is a slight increasing tendency in the annual duration with this again occurring primarily in the mixed regime and likely related to the increased number of events. The event volumes and durations are decreasing with this occurring primarily in the mixed regime. Both the annual volume and event magnitude do not show trends that are field significant.

Multi-temporal trend results are summarized with a collection of graphs constructed for each flood variable; Fig. 2 shows the results for the number of events. Each figure contains eight graphs with increasing and decreasing trends in the left and right columns, respectively, and all stations, nival, mixed, and pluvial stations representing the rows, from top to bottom. Within each graph, the vertical axis represents different starting years and the horizontal axis different ending years, each in five year increments. The shading of the cells represents the proportion of sites with a significant trend (5% local significance level) for the corresponding start and end years. Field significance is indicated by the white symbols inside the cells. The cells along the diagonal are each for different 30 year periods, each row below contains an additional five years of record, and the entry in the lower right corner of each graph gives the result for the entire 1916 – 2015 period, the period for which results were presented in Table 1.

Fig. 2 reveals that the increasing trends in the number of events largely originate with the mixed regime stations. The largest number of trends occurs in periods that end in 2015 with the strongest of these periods being the period that starts in 1916 (i.e., the complete data record). There are other periods of enhanced trend activity, particularly periods ending in the 1980s and early 1990s. Both the nival and pluvial stations also exhibit periods for which field significance is attained, although these periods do not exhibit the same degree of temporal grouping as is the case for the mixed regime and all stations. While there are many

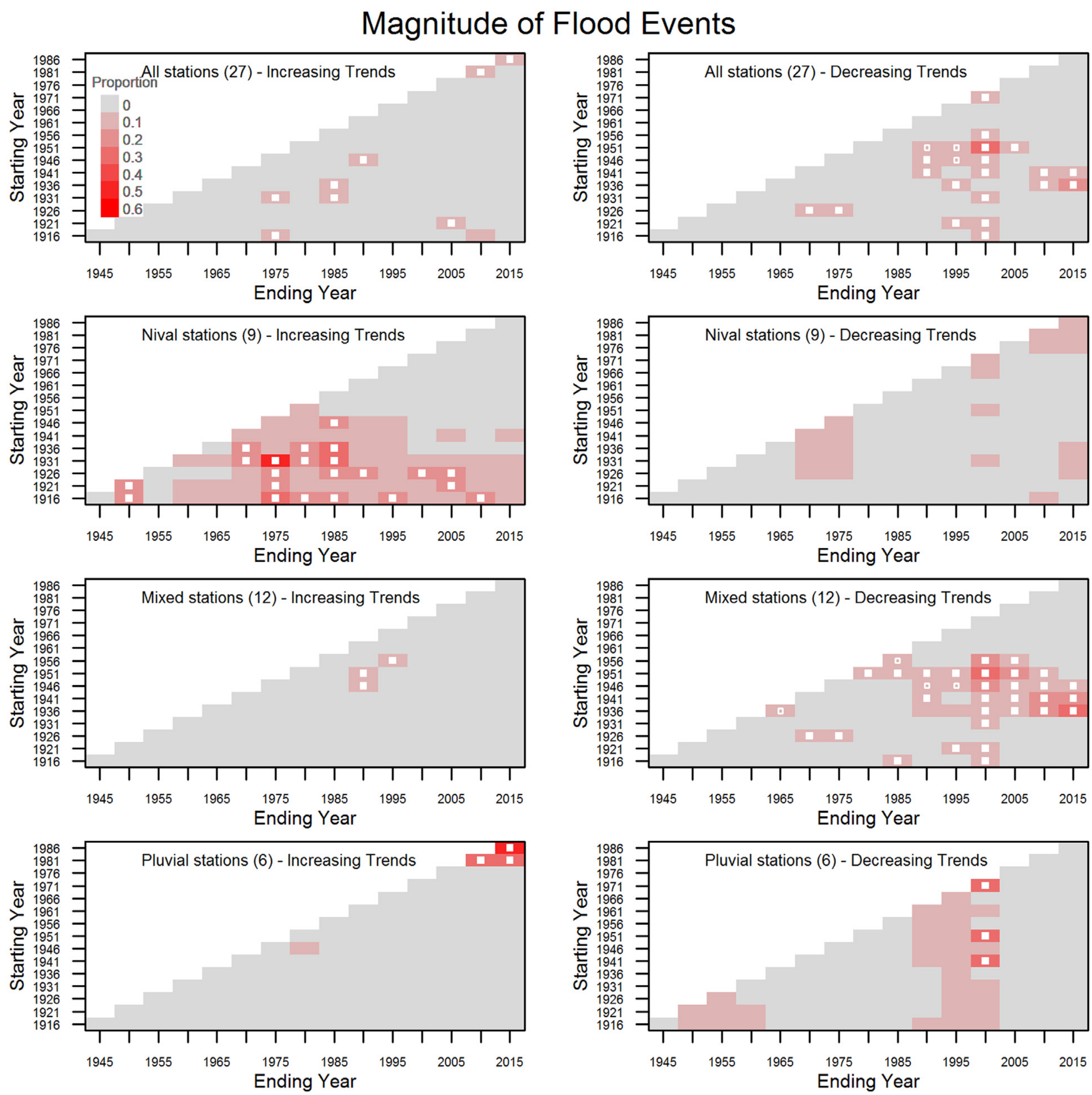

Fig. 8. Same as Fig. 2 but for event magnitude.

fewer decreasing than increasing trends, all four graphs on the right include time periods with a field significant number of decreasing trends.

Fig. 2 shows aggregated trend results indicating significant trends for different time periods. Station trend behaviour for individual stations for selected time periods can be examined as in Fig. 3. The rows in the matrix in Fig. 3 correspond to the stations while the columns are different time periods. The stations are ordered from top to bottom with nival, mixed and pluvial stations grouped together and within each group, the stations are ordered from east (top) to west (bottom) as in Table S1. The nival regime stations are further delineated into mountainous nival stations (lower part) and non-mountainous nival stations (upper part). The pluvial regime stations are further separated into the four east coast stations and the two west coast stations.

In the station trend plots, the time periods for the left half of the figure show the results for time periods starting in 1916 and ending in the years 1945 to 2015 in increments of five years (30, 35, 40, …); this is equivalent to the bottom row in the multi-temporal plots. The right half of the figure shows time periods ending in 2015 and starting in 1986 to 1916 (from top to bottom), again in increments of five years (30, 35, 40, …); this is equivalent to the last column on the right in the multi-temporal plots. The colours in the plot show the trend strength with red indicating increasing trends and blue indicating decreasing trends; statistical significance is indicated by a white diamond. The trend strength is linearly rescaled using p-values from the trend test such that trend strength of −1.0 is a highly significant decreasing trend (p-value of 0.0), a trend strength of 1.0 is a highly significant increasing trend (p-value of 0.0) and a trend strength of 0.0 indicates no trend. Fig. 3 shows the predominance of significant increasing trends for the mixed regime over most time periods. These results also indicate that the trend behaviour for individual sites is not constant and in fact there are stations that exhibit both significant decreasing and significant increasing trends for different time periods. This can be seen in four of the mixed regime sites and also one of the west coast pluvial sites. It is also noteworthy that the more easterly nival regime stations (non-mountainous) display

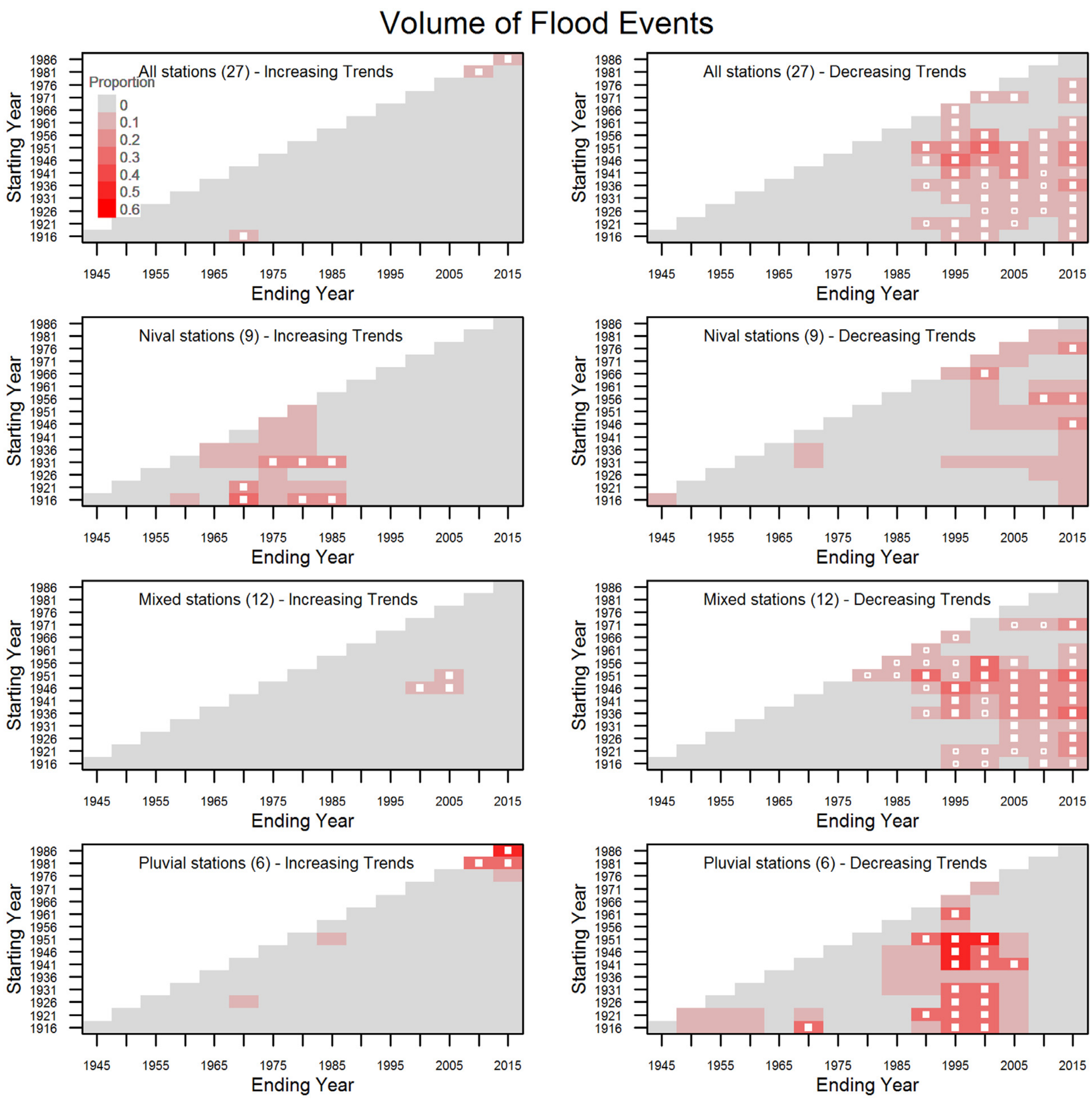

Fig. 9. Same as Fig. 2 but for event volume.

trend behaviour that is similar to many of the mixed regime stations; the same can be said of the east coast pluvial stations. In both cases, this implies that these stations reinforce the view of hydrologic regime as a continuum as opposed to discrete categories with these stations being more towards the mixed regime part of the hydrologic regime in spite of being classified as nival or pluvial.

Fig. 4 presents the multi-temporal trend results for the max magnitude. The results in Fig. 4 demonstrate the dominance of the nival regime in contributing to trends for this flood variable, and that nival trends are offset by a lack of trends for mixed and pluvial stations. It is also apparent that the trend activity in the nival regime is not concentrated in records that end in 2015; periods ending in the mid-1970s and mid-1980s exhibit the greatest concentration of significant trends. There is clearly considerable variability in the trend results for this variable. The results for the increasing trends for the pluvial regime rather dramatically illustrate the perils of relying on a comparatively short, but still contemporary, record. The 1986 and 1981 to 2015 periods (upper right corner) show a strong concentration of significant increasing trends but these are the only periods for which there are a field significant number of increasing trends in the pluvial regime. In fact, for the pluvial stations, there are more periods with significant decreasing trends than increasing trends and more periods with field significant decreasing than increasing trends. The multi-temporal results for average magnitude are similar to the results for max magnitude and are shown in Fig. S1.

The station trend results for max magnitude are shown in Fig. 5. These results reveal that the significant increasing trends in the max magnitude for nival stations require a long record length or an early start year. This implies that earlier periods correspond to lower magnitude events. The significant increasing trends in the east coast pluvial stations that are displayed in Fig. 4 (1981 and 1986 to 2015) are revealed to be an isolated outcome with trend strength in many of the time periods close to the periods noted above indicating no more than weak increasing tendencies. The station trend results for average magnitude are also similar to those for max magnitude (Fig. S2).

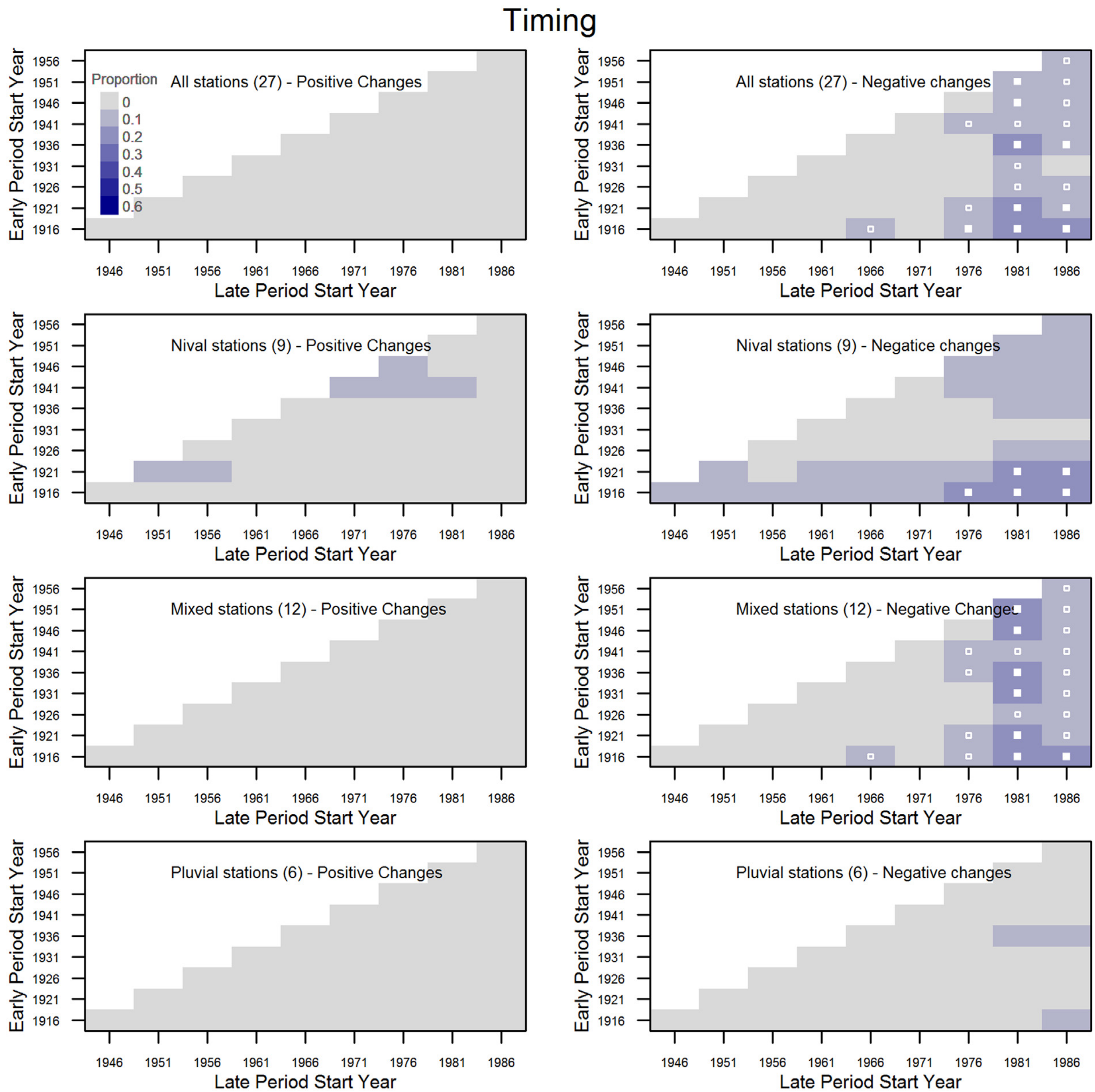

Fig. 10. The proportion of stations showing increasing changes (left column) and decreasing changes (right column) for the timing of events for all, nival, mixed, and pluvial stations and based on all flood events. Boxes along the diagonal represent cases where the early and late 30 year periods are separated by zero years; the length of separation between the periods increases away from the diagonal and is largest in the bottom right corner. Boxes with a solid white square and open square are field significant at 5% and 10% significance levels, respectively.

Fig. 6 presents multi-temporal trend results for the date of occurrence and reveals that significant decreasing trends, implying earlier flood event occurrence, largely occur for periods ending in 2010 or 2015. This implies that earlier flood occurrence is a mostly recent phenomenon. The results reveal significant decreasing trends for both mixed and nival regime stations although interestingly, for both regimes, the period with the largest proportion of significant decreasing trends does not end in 2015 or start in 1916. There are very few time periods with significant increasing trends in the date of occurrence and only 3 of these are field significant. The pluvial regime is the only hydrologic regime for which there are more time periods with significant increasing trends than time periods with significant decreasing trends. There is more of a balance between increasing and decreasing trends than would have been anticipated based on Table 1 although based on the station trend results, many more of the decreasing than increasing trends are significant (Fig. S3).

The annual volume results show only one significant trend for the complete period of record (see Table 1) but the multi-temporal trend results in Fig. 7 reveal more significant trends in other time periods. Of note are the significant increasing trends in: i) the nival regime stations for periods ending in the 1960s through the 1980s; and ii) the mixed regime stations for periods ending in 1965, 1985 and 1990. There are fewer decreasing trends than increasing trends for this variable. The multi-temporal results for annual duration are similar to those for annual volume and can be found in Fig. S4. The station trend results for both the annual volume and annual duration reveal only a modest amount of trend activity (Figures S5 and S6, respectively).

The results for event magnitude (time series of flood exceedences) (Fig. 8) display significant increasing trends for nival stations and significant decreasing trends for mixed regime stations. The latter likely reflects changes from snowmelt to more rainfall dominated systems although this behaviour is not dominate in the entire record implying

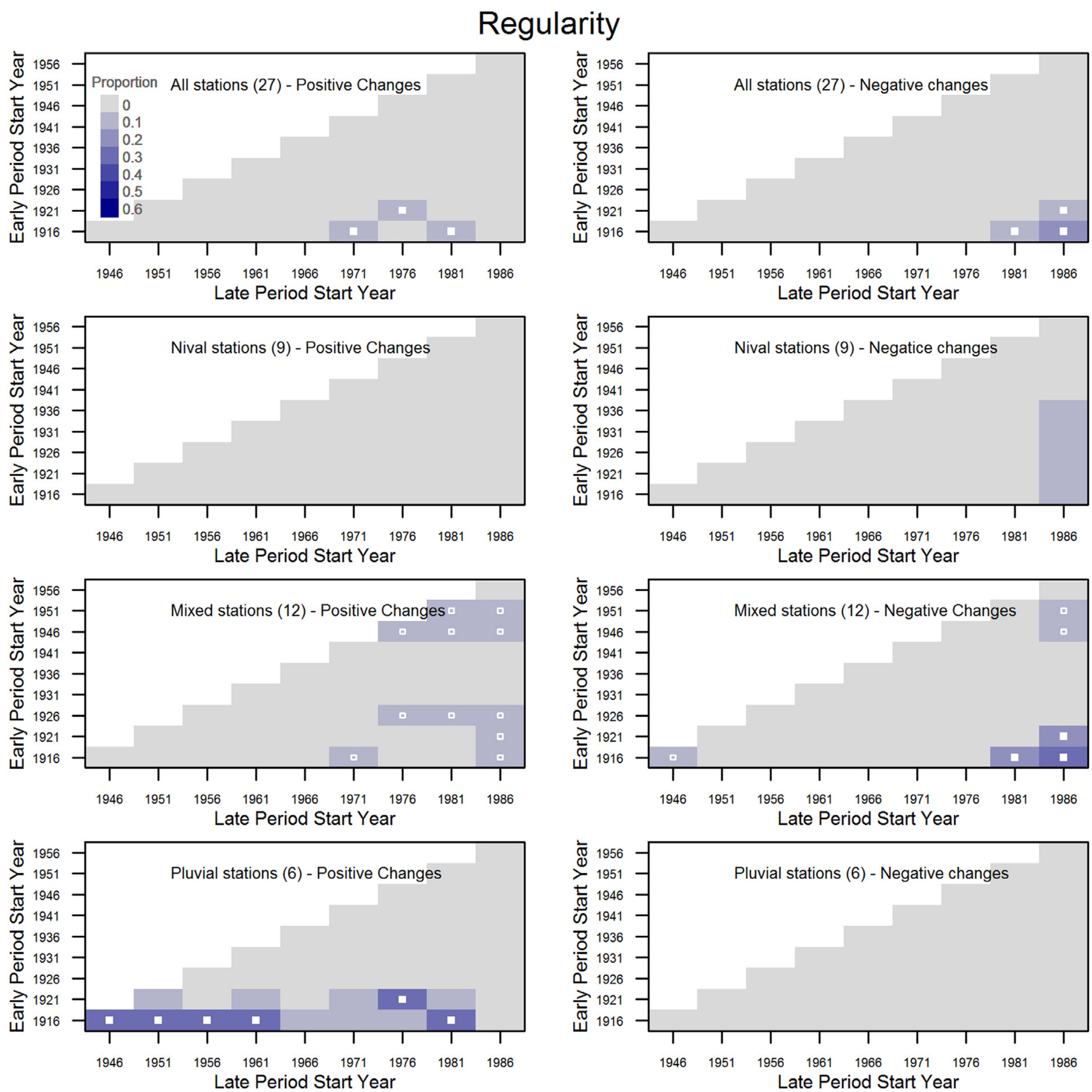

Fig. 11. The proportion of stations showing increasing changes (left column) and decreasing changes (right column) for the regularity of events for all, nival, mixed, and pluvial stations and based on all flood events. Boxes along the diagonal represent cases where the early and late 30 year periods are separated by zero years; the length of separation between the periods increases away from the diagonal and is largest in the bottom right corner. Boxes with a solid white square and open square are field significant at 5% and 10% significance levels, respectively.

variability in the contributing factors. These observations are reinforced by the station trend results that are in Fig. S7.

Fig. 9 presents multi-temporal results for event volume. The significant trends are predominantly decreasing trends from the mixed and pluvial regimes. Trend activity in the pluvial regime is totally absent when looking at periods ending in either 2010 or 2015 and hence these results are missed in the complete period of record results in Table 1. Multi-temporal trend results and station trend results for event duration are very similar to the results for event volume and are presented in Figures S8 and S9.

3.2. Changes in seasonality

Table 2 presents results for changes in the timing and regularity of flood events between two 30 year periods with the early and late periods starting in 1916 and 1986, respectively. Shown in Table 2 is the percentage of stations with a significant change (5% local significance level) with results provided separately for increasing versus decreasing changes. Field significance (10% significance level) is also indicated. Table 2 provides results for all events as well as for nival and pluvial events evaluated separately. Three of the mixed regime stations are not included in the results for pluvial events since these stations have a relatively small number of pluvial events, which led to highly uncertain estimates of the seasonality measures for at least some of the 30 year periods. The number of stations included for each regime and each event type are shown in Table 2.

For the all events case, the results for changes in the timing are very similar to the trend analysis results for the date of occurrence in Table 1, as would be expected, with earlier flood event occurrence for both nival and mixed regimes; these results are field significant at the 10% significance level. The regularity of the events, based on all sites, is decreasing with this result driven by the results from the mixed stations.

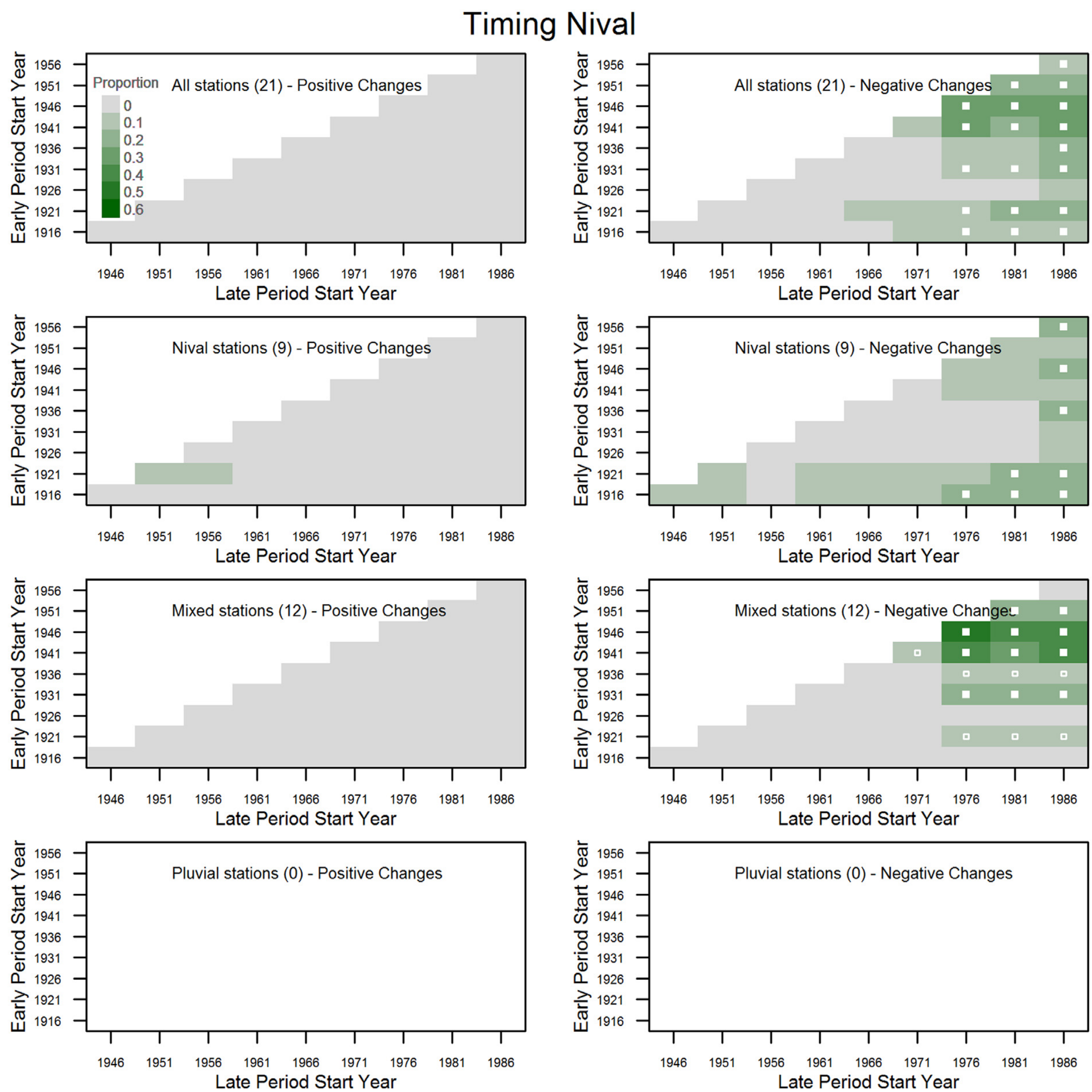

Fig. 12. Same as Fig. 10 but for changes in timing of the nival events.

Table 2
Percentage of sites with significant positive (negative) changes for the seasonality measures between 30 year periods starting in 1916 and 1986. Numbers of stations are shown in [].

	All sites	Nival	Mixed	Pluvial
All events	[27]	[9]	[12]	[6]
Timing	0.0 ***(22.2)***	0.0 ***(22.2)***	0.0 ***(25.0)***	0.0 (16.7)
Regularity	7.4 ***(18.5)***	0.0 (11.1)	***16.7 (33.3)***	0.0 (0.0)
Nival events	[21]	[9]	[12]	
Timing	0.0 ***(14.3)***	0.0 ***(22.2)***	0.0 (8.3)	
Regularity	0.0 (4.8)	0.0 (11.1)	0.0 (0.0)	
Pluvial events	[15]		[9]	[6]
Timing	***13.3*** (6.7)		***22.2*** (0.0)	0.0 (16.7)
Regularity	***13.3*** (0.0)		***22.2*** (0.0)	0.0 (0.0)

Entries in ***bold italics*** are field significant (10% significance level).

Interestingly, the mixed regime stations have field significant increases and decreases in regularity. Decreases in regularity, which are more prevalent, likely reflect an increase in rainfall driven events and a decrease in snowmelt driven events for the mixed regime stations. A transition to flood event occurrence that is more bimodal will reduce the regularity of the events. The increase in regularity for some mixed regime stations could result from stations that exhibit a predominance of rainfall driven events in the later period and hence less marked bimodality in the later period than was observed in the earlier period. There are fewer significant changes for the nival and the pluvial event datasets than were observed for the all event dataset. The nival dataset reveals significant changes in the timing for nival stations with a transition to earlier occurrence of flood events. For the pluvial events, there is an increase in the timing and regularity for the mixed regime stations, implying that the pluvial events in mixed regime stations are occurring later in the year and are more regular in the most recent 30 year period.

The multi-temporal change analysis results for timing based on all flood events are very similar to the trend analysis for date of occurrence; these results are presented in Fig. 10. Station change analysis results (Fig. S10) are similar to the corresponding trend analysis results for date of occurrence and reveal the contributions of nival and mixed regime stations to the observed shifts in flood event timing. Fig. 11

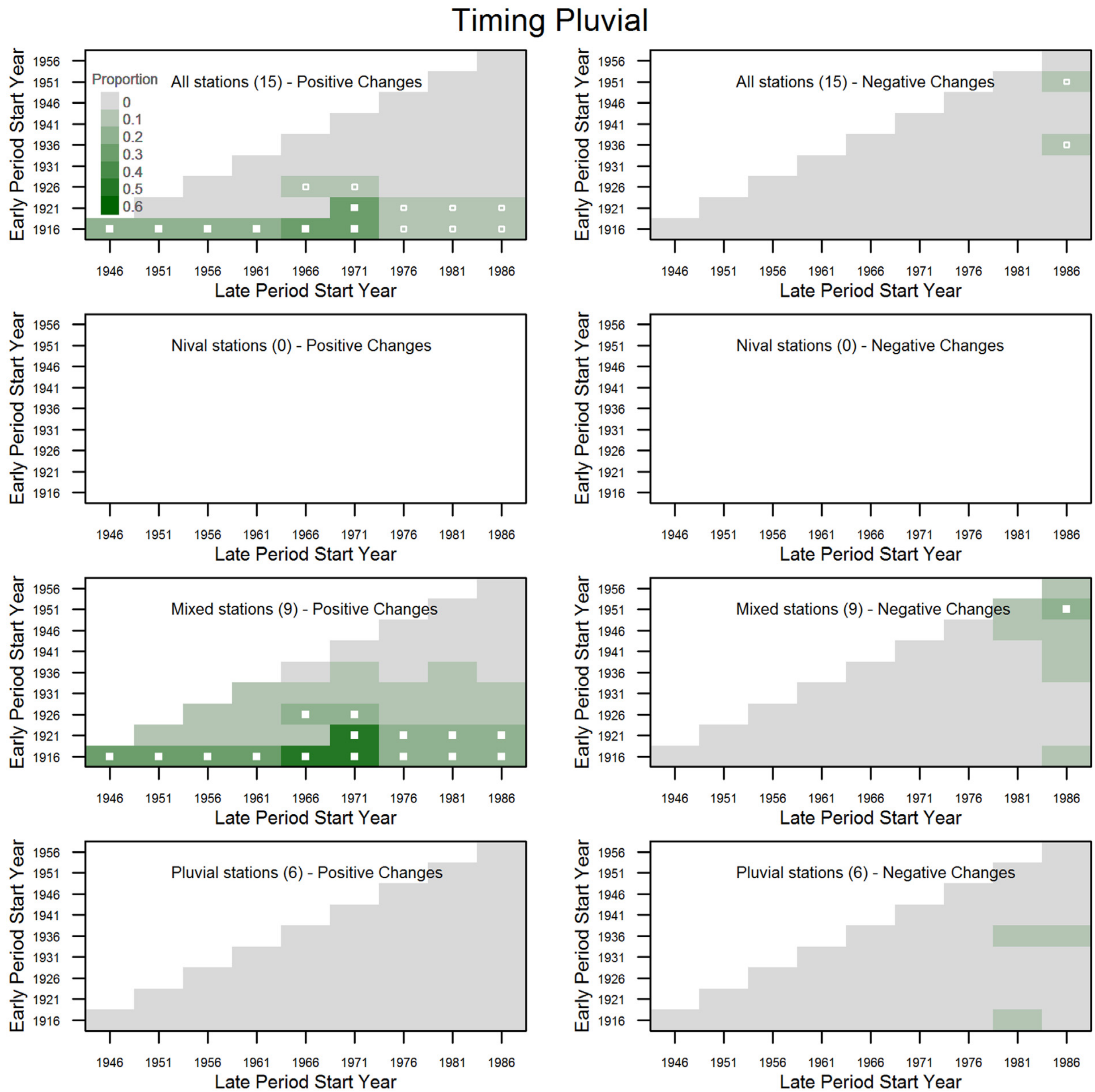

Fig. 13. Same as Fig. 10 but for changes in timing of the pluvial events.

displays the multi-temporal change analysis results for regularity and reveals greater detail in the patterns of regularity changes than can be inferred from Table 2. In particular, for the pluvial stations, for several of the early periods that start in 1916 there are significant increases in the regularity with many of these results being field significant. Greater detail in the change analysis results can also be gleaned from examining the results at the station level (Fig. S11). The increasing changes in the regularity for pluvial stations can be seen to occur in the east coast pluvial stations, which can be considered to be a move towards the pluvial end of the pluvial regime continuum. Hence, the increased regularity can reflect a decrease in snowmelt contributions to the flood events and therefore a decreased bimodality in the timing of flood events. For the mixed regime stations there is also a noticeable difference in the changes in regularity for the more easterly stations in comparison to the more westerly stations again implying that there are different processes contributing to the increases versus decreases in regularity of the flood response for stations in the mixed regime.

Calculating a circular mean date based on all flood events cannot distinguish which flood events are changing. When clusters of nival and pluvial peaks are treated separately, the changes are more robustly identified. The timing of only nival events is dominated by decreasing trends (Fig. 12), and reveals very similar behaviour to the results for all events in Fig. 10. The multi-temporal change analysis for the regularity of nival events reveals very few significant changes (not shown). This implies that changes in regularity for all events (Fig. 11) largely result from changes in pluvial events or from changes in the mix of nival and pluvial events in the early versus the late period.

Fig. 13 shows the multi-temporal change analysis for the timing of only pluvial events and reveals mainly increasing changes implying later occurrence of pluvial events in the more recent period. These changes are occurring in the mixed regime stations with the greatest number of significant changes for late periods starting in the late 1960s and early 1970s. Fig. S12, which displays the station results for the timing of pluvial events, reveals spatial as well as temporal differences in the significant changes. The significant increasing changes in the timing occur exclusively in the more easterly mixed regime sites and several of these sites display both increasing and decreasing changes depending on the start year for the early and late periods.

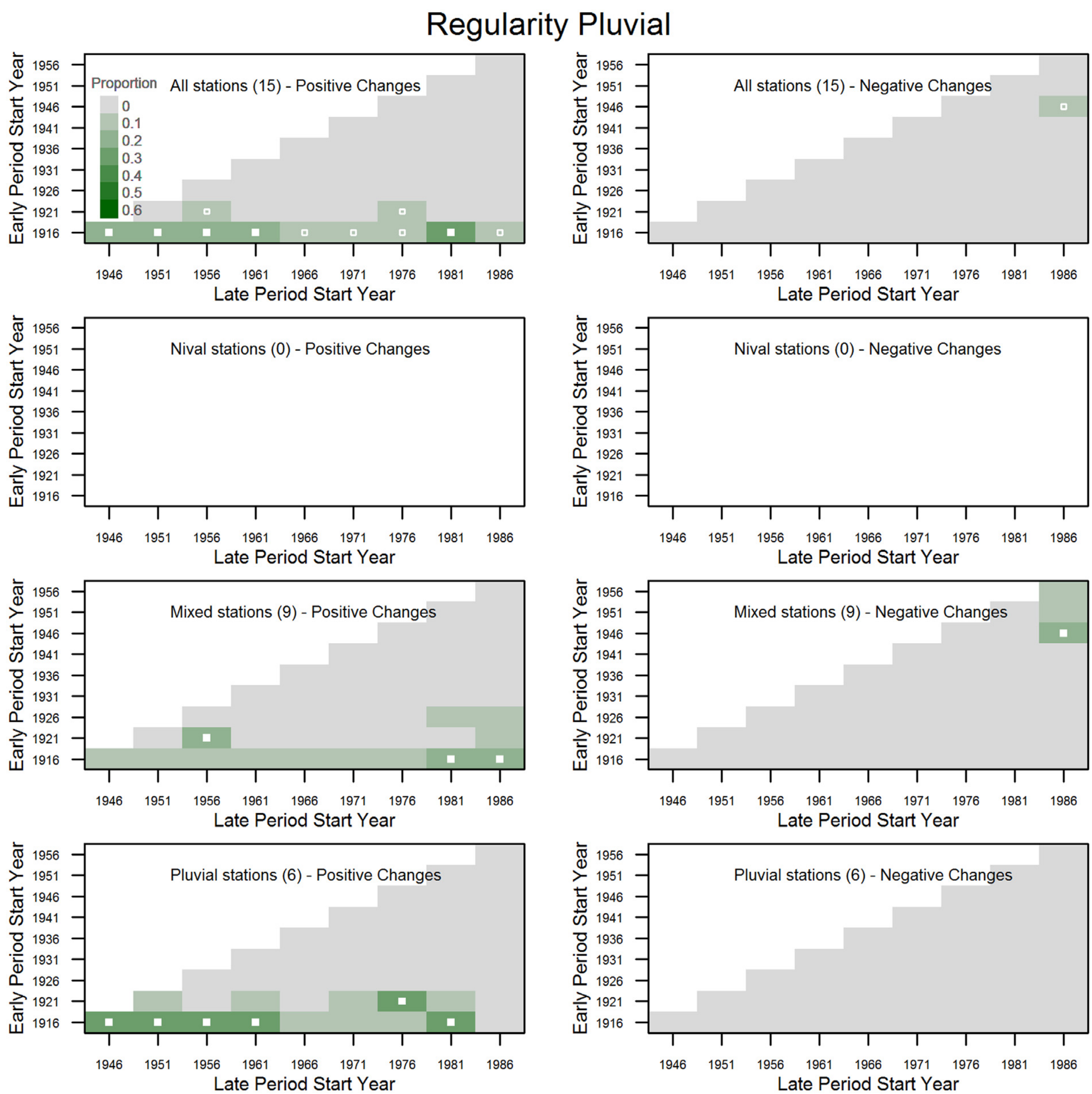

Fig. 14. Same as Fig. 11 but for changes in regularity of the pluvial events.

Multi-temporal change analysis results for the regularity of pluvial events include mainly increasing changes with contributions from both mixed and pluvial regime stations, as shown in Fig. 14. The station analysis results for this variable are shown in Fig. S13 and reveal differences between east and west coast pluvial stations, with the latter demonstrating no significant trends. There is not a strong spatial consistency in the results for the mixed regime stations.

4. Discussion

The trend results based on the entire period of record indicate generally increasing flood magnitudes in the nival regime stations (Table 1, Fig. 4), an increase in the number of events (Fig. 2) and an earlier average date of occurrence of events for the mixed regime stations (Fig. 6), and generally more flood events in the pluvial regime stations (Fig. 2). The multi-temporal trend analysis reveals that trends do not simply get stronger with an increase in record length but rather there are time periods when different flood variables display a stronger trend signal. The trend results at the station level reveal that there are stations for which both significant increasing and significant decreasing trends for a given flood variable are observed in different time periods, implying that both the number and the nature of trends can change between different observation periods. It is therefore important that long term data records be used for trend analysis and that multi-temporal analysis be conducted to ensure that all relevant trend behaviours are captured; trends determined using short periods of records could be misinterpreted with respect to the impacts of a changing climate. With the exception of the increasing number of flood events (Table 1, Fig. 2), few of the variables exhibited a significant trend between 1916 and 2015; yet the multi-temporal trend plots show coherent periods where significant trends exist. The existence of temporal patterns in the behaviour of trends in floods variables has been observed for other study areas as well. Mediero et al. (2015) examined long streamflow records across Europe and used a multi-temporal trend analysis approach to identify time periods with significant flood trends based on a grouping of the stations into five large-scale, geographic regions. Mediero et al. (2014) conducted multi-temporal trend analysis for long record stations in Spain

and observed distinct flood-rich and flood-poor periods from a roughly 70 year period of record. Merz et al. (2016) investigated the nature of flood-rich and flood-poor periods for rivers in Germany based on long record periods and found less temporal clustering for more severe flood events in comparison with the clustering observed in more frequently occurring flood events. Liu et al. (2017) found temporal clustering of floods for the Poyang Lake basin in China and related flood magnitude and occurrence rate to a number of climate indices. These results are generally supported by the results from our work, although it should be noted that not all of the studies above used data from a reference hydrologic network.

Changes to the seasonality measures based on the period of record are characterized by: earlier occurrence of flood events, particularly for nival and the snow component of mixed regime stations; changes in the regularity of flood events, particularly for mixed regime stations; later occurrence of pluvial flood events for mixed regime stations; and increases in the regularity of pluvial flood events for mixed regime stations (Table 2, Fig. 11). These results imply that there are changes occurring in the nature of flood events with a decreased predominance of snowmelt events and an increase in rainfall driven events, including rain-on-snow events. The present analysis does not distinguish between rain-on-snow and snowmelt peaks with respect to timing.

Averaging the date of all POT events, even using circular statistics, may not be sufficiently robust or specific as the result only deals with the average event occurrence and is affected by the location and frequency of events. Conducting the analysis separately for clusters of nival (Fig. 12) and pluvial events (Fig. 13) gives more robust results for each specific flood generating process. The changes shown in Fig. 12 are consistent with an earlier onset to snowmelt and in Fig. 13 with an increased frequency of winter rainfall. This behaviour is apparent with some of the nival regime stations and particularly noteworthy in the mixed regime stations. As with trend analysis, multi-temporal seasonality change analysis reveals time periods of greater changes in seasonality. Other researchers have also found a prevalence of changes in the seasonality of flood response especially from cold region areas. Matti et al. (2016) examined 18 watersheds in Sweden, including some with long record lengths, and found that many of the watersheds are expected to experience a change from snowmelt dominated flood response to a more rainfall driven flood response. Matti et al. (2017) studied 59 Scandinavian watersheds that were segregated by hydrologic regime and found evidence for shifts in the flood seasonality for snowmelt dominated regimes. These outcomes are consistent with the seasonal change analysis presented in this paper.

Analysis of trends in temperature and precipitation data for the study area (Zhang et al., 2000; Turner and Gyakum, 2010) indicate generally wetter and warmer conditions with trends in spring and winter being stronger than in other seasons. Zhang et al. (2000) further indicate that the ratio of snow to total precipitation has generally increased, although this is more prevalent in the northern part of Canada, an underrepresented area in our study. These results are consistent with the findings in this work of changes in flood generation processes particularly for snowmelt events. Increased temperatures can alter the mix of rain and snow and affect the overall accumulation of snowpack during the winter season. Hamlet et al. (2005) found that widespread warming in western United States and southern and western parts of Canada led to decreases in spring snow water equivalent (SWE); however, they also found that at higher elevation sites, spring SWE is increasing due to increases in precipitation. The complex behaviour of snowpack accumulation and ablation, particularly in mountainous regions, is a confounding factor in the investigation of climate change impacts on flood events within cold regions. Our future work will look at expanding our current network of sites to further explore changes in flood generation within cold regions.

5. Conclusions

An examination of trends in flood variables and changes in flood seasonality point to increases in flood magnitudes and earlier occurrence of flood events for nival regime stations while mixed regime stations are characterized by an increased number of events, an earlier occurrence of events, a decrease in event volume and duration as well as a decrease in regularity. The pluvial regime stations experience an increased number of events but in general the pluvial regime stations and the pluvial flood events exhibit very few significant trends in flood variables or changes in flood seasonality. These results collectively suggest that flood events are affected more by changes in flood generation processes (snowmelt versus rain-on-snow versus rainfall events) as opposed to widespread increases in the magnitudes of precipitation events. The trends and changes noted can be inferred to be climate driven since all data are from reference hydrologic networks and therefore the watersheds should be only minimally affected by non-climatic changes.

The results from the multi-temporal analysis conducted in this work emphasize the importance of long record sites for conducting trend and change analyses. The existence of sites for which both significant increasing and significant decreasing trends or changes have been observed for different analysis time periods implies that long record lengths are essential. Even with long record lengths a multi-temporal analysis is desirable to extract as much information as possible regarding trends and changes from the available records.

The non-constant nature of trends and changes in flood behaviour imply that flood-rich and flood-poor periods exist within the complete period of record, as has been noted for other geographic areas of the world. Future work will look for relationships between flood-rich and flood-poor periods and various drivers of flood activity, including large scale climate indices.

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Competing interests

The authors declare no competing interests.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2018.08.017.

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